PROPOSED DESIGN OF A

TACTICAL RECONNAISSANCE SATELLITE SYSTEM

THESIS

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Preface

The purpose of this study was to propose a space-based system that would be able to accomplish the mission of tactical reconnaissance. A system was derived using similar proposed systems and existing technology and hardware. Alternative systems, varied mostly in cost and threat scenario, were weighed against system criteria and constraints, with the best alternative being the most expensive alternative.

This paper would not have been completed, in this form, if it weren't for the efforts of many people. I would like to thank my advisor, Maj T.S. Kelso, for letting me have my way on the approach to the problem; my committee member, Maj Bruce Morlan, for his support; Lt Col Howard Evans, who helped me understand remote sensing in the way that only he could; Col "Sammy" Miyamasu, who kept after me to work and who supplied much needed system constraints; and Maj Charles Banning, whose TACSAT inputs were indispensable. Finally, I have to thank my wife, Gwen, for her love and support during this time, also her quiet perseverance was unusual and refreshing. Mostly, though, I need to thank Gwen for not waking me in the middle of the night when I should be taking care of Jordan.

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Abstract

Tactical reconnaissance is a much needed wartime asset, yet with the planned deactivation of all active-duty RF-4C squadrons world-wide there appears to be a gap in this country's war-fighting capability. This study proposes a system which utilizes a constellation of small tactical satellites and mobile ground receiving stations that can fulfill the tactical reconnaissance mission. A literature review gives background information on resolution variables, the RF-4C, space reconnaissance, and sensing technologies. After defining system requirements and constraints, a basic system concept is determined. Three alternative systems, separated mostly by threat scenario, technology, and cost, are evaluated using Athey's "Systematic Systems Approach." The selected satellite's sensors consist of a multispectral imager and a SAR. The satellite will be launched by the Pegasus air-launched booster for flexibility, survivability, and responsiveness. Initially, four satellites will be placed in a circular low-earth orbit (LEO) for training, with four more in-orbit spares, although, twelve more will be stored as ground spares and can be placed into any LEO that is needed. The ground receiving unit will be the Mark IVB tactical terminal which will be located in communications vans at the lowest echelon with a planning staff wherever troops are deployed.

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I. *Problem Statement and Methodology*

Background

Tactical reconnaissance (Tac Recce) is a vital part of military operations. An understanding of Tac Recce is needed in order to appreciate it. Tactical reconnaissance is surveillance which gathers military intelligence about unknown states of the world for theater-level decision makers. Tactical reconnaissance is similar to strategic reconnaissance in that both gather military intelligence, whether by photo-optical or electronic means. Strategic reconnaissance differs from tactical in the use of the information gathered. Even though the same information is presented to the strategic and tactical decision makers, if the information is used to manage the big picture, the overall war effort, or updating an ongoing database, then the information is said to be strategic reconnaissance. In contrast, if the information is used for theater conflict, the short-term battle, or the state of nearby enemy forces, then the information is said to be tactical reconnaissance.

A short history of tactical reconnaissance may be helpful in understanding the concept. Men suspended over the battle in balloons were used in the American Civil War first as artillery spotters, then as intelligence gatherers. These men provided the army commanders with enemy troop movements and cannon positions. During World War I, cameras were brought onboard aircraft and balloons to photograph

enemy forces and report on battle damage that both sides had inflicted on industries and bridges. This same concept is still used today, with different platforms employing sophisticated sensors, to gather information on the opposing forces in order to provide decision makers with valuable intelligence. The McDonnell-Douglas RF-4C aircraft is the primary tactical reconnaissance platform in the US military today. The RF-4C has been supplying all requestors with photo-optical, infrared, and electronic intelligence worldwide since 1963.

Use of the intelligence acquired provides more insight into Tac Recce's importance. Given the state of opposing forces, Army company commanders can deploy their troops more effectively. Given soil conditions, Army engineer squadron commanders can select the best location to construct a river crossing. Given battle damage assessment, air group commanders can redirect strike packages in order to maximize effectiveness. These are only a few of the many critical uses of Tac Recce today.

In 1987, there were eight active duty US Air Force Tac Recce flying squadrons worldwide. By the end of fiscal year 1990, there will be two squadrons. By 1993, there will be none. Unfortunately, there is no follow-on aircraft planned to replace the aging RF-4C. This signals the end of Tactical Air Command's (TAC) reconnaissance mission. This significant reduction in intelligence gathering forces for theater commanders will be a hindrance in future armed conflicts. The problem then becomes what system will do the mission of Tac Recce in the future?

A clue comes from the recent retirement of the Lockheed SR-71 strategic reconnaissance aircraft. The official stance on retiring the

SR-71 is that space assets can do the same job for less money (31:24). Since there is no follow-on aircraft to the RF-4C, it might be assumed that space assets are also going to accomplish the mission of Tac Recce.

Unfortunately, the CIA-run surveillance satellite system has been ineffective in getting needed information quickly to the field. Even with the deployment of newer satellites that do essentially the same thing, such as the AFP-731 which is postulated to be the replacement for the KH-11 surveillance satellite (5:22), intelligence will still not get to the user in the tactical world in a timely manner. What the military forces need is a separate satellite system whose only mission is to accomplish tactical reconnaissance.

Scope and Limitations

This paper will present a broad overview of an entire system needed to meet the objective of a space-based satellite system which can accomplish the Tac Recce mission. The sensor is the most important component of the satellite; therefore, emphasis is given to this component in the literary review and in determining a proposed satellite system. Other components will be overviewed, to include determining requirements that must be met for a functioning satellite system. The system components will then be put together optimizing the system requirements within the constraints.[1] The basing and launching options, as well as the user interface, will be analyzed to the extent of determining the best overall system. System cost will be addressed as a goal, yet quantitative cost analysis will not be accomplished in this paper because of the magnitude of such an effort and some of the

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[1]System requirements and constraints are presented in Chapter 3.

undeveloped advanced technology would be difficult to cost realistically at this time.

Certain aspects of the RF-4C mission and most of space-based surveillance are classified, therefore this paper will be restricted to unclassified aspects of imaging capabilities, that is photo-optical and infrared for the RF-4C and photo-optical and radar mapping/multispectral scanning for space assets.

Objective

The purpose of this research is to propose a design of a satellite system that will meet the requirements of tactical reconnaissance and is separate from existing space-based surveillance systems. In accomplishing this objective, this research will:

1. Determine what the requirements are for a tactical reconnaissance satellite system.
2. Determine what the major constraints are in developing and procuring a satellite system.
3. Analyze current technology that could be used in space-based reconnaissance sensors, such as photo-optical, infrared, radar, and microwave remote sensing.
4. Determine the satellite basing and orbit options that best support the established requirements and constraints.
5. Determine the booster to deploy the satellite which optimizes the established requirements and constraints.
6. Determine the ground user equipment and the deployment of the equipment, including command and control of the satellite, which meets the established requirements and constraints.

Methodology

In fulfilling the above objectives, this researcher:

1. Researched current capabilities by contacting Air Force Space Systems Division, Army Space Institute, and Army Space Command, and interviewing requirements/procurement officers concerning the present system and ways to improve it.

2. Contacted and interviewed the Director of Special Projects, Electronic Combat and Reconnaissance SPO, concerning possible constraints in designing a satellite system.

3. Researched projected capabilities by receiving information from the Army Space Institute, published books and journals, and other unclassified sources about existing and future remote sensing equipment and determining alternatives based on established requirements and constraints.

4. Researched potential launch options (East Coast, West Coast, or over water), basing options (quick launch, constellation with or without on-orbit spares), and orbit characteristics (apogee, perigee, inclination, and orientation) against requirements and constraints and determined alternatives.

5. Researched potential launch systems against satellite weight and orbit requirements and determined alternatives.

6. Researched potential ground equipment (receiver antennae, computer processor, relay systems to field users) through Army Training and Doctrine organizations in Army Space Command. Also researched existing Army equipment that could receive and transmit digital information, and establish ground network with existing equipment.

7. Established alternative Tac Recce satellite systems, with differing cost guidelines, for final evaluation.

8. Evaluated and ranked alternative systems using the methodology of the "Systematic Systems Approach" by Thomas H. Athey (4).

II. Literature Review

In order to appreciate the requirements of a tactical reconnaissance (Tac Recce) satellite system, this literature review will present background information on resolution variables, the RF-4C, space reconnaissance, and remote sensing technologies.

Resolution

In discussing tactical reconnaissance, resolution must be defined. Resolution is the one thing that the intelligence community holds most dear. By definition, it is the ability to ascertain detail. For example, in a photograph (or other type of imagery) containing two barrels set one foot apart, if a photo interpreter (or other intelligence analyst) can discern the two barrels, then the photograph is said to have at least one-foot resolution. The kind of resolution spoken about in tactical reconnaissance is the smallest amount of detail that can be determined from the imagery. Overall system resolution is affected by the resolution of each of the system parts: the optics, the film or recorder, the contrast, and so on (12:Chapt 5,5).

The resolution of target imagery is called ground resolution, and is determined by the slant range to the target, the focal length of the camera, and the lens/film resolution (Rlf). Of these, Rlf is the most unfamiliar term. It is a quantity that is inversely proportional to the sum of the lens resolution and the film resolution, and is measured in lines per millimeter (ln/mm). For example, if a lens has a resolution capability of 100 ln/mm, then it can produce 100 separate lines in one millimeter of film. This is determined by the optical quality of the glass

lens as well as the aperture size, or f-stop (12:Chapt 5,8). Better optics give better resolution; unfortunately, cost and technology limit available optics.

Film resolution, on the other hand, is generally based on granularity, or grain-size (12:Chapt 5,8). In other words, the smaller the grain of the film, the better the resolution. Therefore, good optics matched with poor film produces poor resolution.

One other factor that influences Rlf is target contrast. Target contrast is the difference between the target and its background. White on black is an example of high contrast, while brown on black is lower contrast. Rlf is usually given in two values of contrast. High contrast has a contrast ratio of 1000:1, yet is rarely used in intelligence because the real world is not made up of black and white. Low contrast, though, is very useful because it has a contrast ratio of 1.6:1, which can determine a difference in grays (which is closer to the way things are in the real world), and takes into account haze, which often degrades imagery (12:Chapt 5,8).

From experience, focal length is another important aspect of resolution. As on an average household 35-mm SLR camera, a longer focal length brings more detail into focus. Yet, there is the sacrifice of obtaining less coverage. In other words, at the same slant range from the target, the target will appear bigger in the imagery, giving more detail, yet a smaller percentage of the previous coverage will be seen. Generally, the longer the focal length of the camera lens the better the resolution of the final product. Resolution, then, is based on the specific camera, optics, focal length, and film that make up the system.

Resolutions given herein are considered average for the system being discussed.

McDonnell-Douglas RF-4C Phantom II

The Air Force currently accomplishes Tac Recce with the RF-4C. In order to appreciate a proposed space-based tactical reconnaissance system, an understanding of the current Tac Recce system is required. The elements covered in this review are mission, capabilities, system process, and limitations.

Mission. As stated above, tactical reconnaissance is that which pertains to the theater level of operation. This is opposed to strategic reconnaissance, which is the big picture--God's eye view of the conflict/operation; tactical reconnaissance concerns itself with the little picture--this battle, the next objective, etc. Therefore, the mission of the RF-4C is to gather intelligence on the theater scale of operations. The RF-4C has several users of its intelligence. It provides targeting information and battle damage assessment of targets for Air Force fighters. The biggest requestor for tactical intelligence, though, is the Army. The Army, on the division level, is always looking for the best place to cross the next river, the best place to push through enemy lines, or locating where the enemy is massing for a strike of their own. The RF-4C provides such intelligence to all its users with day/night imagery through a well established intelligence network.

Capabilities. The RF-4C is an all-weather day/night reconnaissance platform. The photo-optical sensors which can be carried range from the T-11 high-altitude (20,000 ft AGL (above ground level)) framing camera, to the "jack of all trades" framing camera, the KS-87, which can

be fitted with lenses ranging from 3" to 18" focal lengths, to the KA-56, a high-speed, low-altitude, panoramic camera (600 knots ground speed and 200 ft AGL without overspeeding the camera and causing a camera failure).

Framing cameras and panoramic cameras add to the RF-4C's flexibility. Framing cameras produce products which have constant scale. Scale is the property which allows photo interpreters to accurately measure specific dimensions for proper measuring of targets. Panoramic cameras, on the other hand, are useful in maximizing coverage. These types of cameras use prisms to refract the light radiating from the target in order get its coverage. This is similar to the so called "fish-eye" or wide-angle lenses of popular photography. The KA-56 camera, for instance, captures, on a single frame of film (which measures 4.5" x 12"), a picture from horizon to horizon (180° scan).

Target resolutions from these cameras range from 6", for the high-altitude camera, to better than 1/2", for the low-altitude panoramic camera.

There is, of course, night imagery capability. It is well known that in the last major armed conflict, almost all of the supply and troop movement was accomplished at night. With the addition of the AAD-5 infrared camera system in the RF-4C, such night reconnaissance targets can be acquired even at high-speed, high-maneuvering, low-altitude flight, with surprising resolution.

This assortment of cameras, lenses, and resolutions gives the RF-4C a lot of flexibility in attacking targets and ultimately returning with the required intelligence (12:Chapt 5,1).

In accomplishing its mission, the RF-4C is adept at ingressing into hostile territory without fighter escort, or airborne support assets of any kind, which further enhances its flexibility and timeliness to target requests, because it is not tied to other assets or other timetables. Delaying takeoff in order for the F-15 cap to be established, or waiting for the next F-16 strike package to follow into the target area, or even replanning the mission to use EF-111 jamming corridors are not necessary to get the job done quickly. Even though the RF-4C is aged compared to other Air Force fighter assets, it is a proven and reliable platform, and is well suited for its mission.

System Process. In order to fully appreciate the role of the RF-4C in theater operations, an understanding of the process of gathering tactical reconnaissance, which will take place in times of conflict, is required.

The most prevalent scenario, with the Army as the requestor, will be described here. The division commander wants intelligence on enemy movement in a certain sector. The Air Liaison Officer, who is a rated Air Force officer specially trained to deal with Army requests, translates the Army's desires into Air Force targets and passes the information to the Tactical Air Control Center (TACC), who in turn tasks the nearest tactical reconnaissance unit to acquire the information. RF-4C crews, on alert, can respond to "immediate" requests and can plan the mission and be in the air within two hours of being tasked. When the RF-4C returns, the Photographic Processing and Interpretation Facility (PPIF) is required, not only to develop the film, but also to gather the required intelligence and send a report to the requestor within 45 minutes of landing. This information is sent directly to the requestor via

computer over existing communication lines, adding to the timeliness and flexibility of the system. This equipment is mobile both at the RF-4C deployed location and at the Army's location, so that intelligence is not delayed by the fluidity of battle lines.

Limitations. There are, however, limitations. In the big picture, the system would work better if the Army could obtain their own intelligence. This would cut down on the delay caused by the red tape of processing requests through two branches of the armed services. Even though the RF-4C can achieve its objective and transmit intelligence to the requestor within a matter of hours, typically it takes two days for the request to reach the RF-4C crew. Timeliness of the intelligence is therefore hampered. Many things can happen in the days it takes to process the paperwork.

Further, the photo-optical process is time consuming, facility dependent, and expensive. Electro-optical sensors for the RF-4C are presently being developed to alleviate this deficiency (34:41-42). This would reduce the size of the PPIF (videotape does not need large chemical vats) and the image could be electronically transmitted to the requestor in addition to the written report. A picture is worth a thousand words, enhancing intelligence to the user. Yet, that is in the future and the RF-4C may not even be refitted with the new sensors because the fleet is being retired.

There are also limitations associated with the crew of the RF-4C. The same crew cannot work continuously for long periods of time without degradation. Physical and mental fatigue are dangerous in the flying arena. There is also crew error to consider. Aircrew members,

being human, do make mistakes, especially when confronted with enemy fire.

In addition, targets have been known to be dropped due to weather. If the aircraft can't take off, it can't get its targets. Even though the RF-4C can underfly cloud decks, it can't underfly ground fog.

Of course, sensors can, and do, fail. Having crews in the planes to do visual reconnaissance is the obvious backup to sensor failure. Visual reconnaissance, however, is virtually impossible at night.

Additionally, because there are crews in the aircraft, not all targets are attempted due to the overwhelming defenses that must be breached. Crews are hesitant to fly, and commanders hesitant to deploy, into very heavily defended areas. The RF-4C is a fine platform, and while it does achieve its mission, maybe it is because of these kinds of limitations that it is being phased out of the Air Force inventory.

Space Reconnaissance

For the purposes of this paper, space reconnaissance is defined as the assets, including satellites and ground stations that track and control them, that observe the earth's surface from space using means of photo-optical, electro-optical, microwave, and multispectral imaging. An introduction to the current space reconnaissance system is required in order to understand the need for a new space-based Tac Recce system. This paper will provide background information on current systems and intelligence dissemination.

Current Systems. Space reconnaissance has come a long way since the Discoverer[1] series of satellites. The United States has made technology the driving force of satellite development. Technological quality over quantity has been the theme of the US space assets. This can be seen in the way the US conducts the business of space reconnaissance today.

The current crop of reconnaissance satellites includes the KH-11, the KH-12, and Lacrosse. First launched into orbit in December 1976, the KH-11 was the first "real-time" imaging satellite. This meant that electro-optical images were datalinked down to a receiving station almost as the event was happening (maximum lag time of 90 minutes from satellite to ground station). This substantially cut down the two- to three-week wait that the intelligence community endured with the bucket-dropping[3] KH-9s (8:234), the KH-11s' predecessors. Even though the KH-11 sustained a higher orbit than the KH-9 (300-km perigee versus 160 km), the target resolution is said to be as good as the KH-9. Theoretically, the optics of the KH-11 can achieve two-inch resolution (8:239). *Jane's Spacecraft Directory 1986* describes the KH-11's resolution capabilities as being able to

> distinguish military from civilian personnel, while its infrared and multispectral sensing devices can locate missiles, trains and launchers by day or night, and distinguish

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[1]The Discoverer series of satellites were the CIA's first attempts into the field of space-based reconnaissance. First launched in 1959, it took twelve unsuccessful attempts before Discoverer 13 produced usable intelligence. These early reconnaissance satellites ejected a capsule, consisting of the camera and exposed film, that was recovered either in flight by the Air Force, or after splashdown by the Navy (8:104-106).

[3]The KH-9 satellite contained a series of capsules, or "buckets," of film, which were ejected after exposure (8:105).

> camouflage and artificial vegetation from real plants and trees. (35:302)

It can also see through cloud cover (35:302). KH-11s work in pairs covering the same target area twice a day, in the morning and afternoon, and have been doing so for more than a decade (26:134). The lifespan of a KH-11 satellite is one to two years. This is significantly longer than the less-than-a-year lifetime of previous reconnaissance satellites (35:302). The quality of US technology permits the deployment of a limited number of high-flying, long-lasting reconnaissance satellites.

The recently deployed KH-12 is the follow-on to the KH-11. It was designed to be a single system that will serve all users (19:18). It is the state of the art in surveillance satellites and is said to have at least as good resolution as the KH-11 (26:133). Major improvements postulated include a lens the size of the Hubble Space Telescope lens and refueling capability. This sensor, launched in early 1990, has an aperture of 2.4 meters and a focal length of 24 meters, giving it very good resolution if it were to be turned toward the earth (as in the KH-12) (22:46). Refueling capability is an important improvement because it gives the satellite controller more fuel for maneuvering, which translates to more flexibility in targeting and eluding certain types of anti-satellite weapons (8:91-92). With the addition of the KH-12s' technology into the space reconnaissance fleet, more reconnaissance flexibility is in orbit.

The other type of reconnaissance satellite in orbit today is known as Lacrosse. It is postulated to contain microwave remote sensing capabilities, also known as radar mapping. Microwave remote sensing is the general term for surveillance in electromagnetic frequencies outside the visible spectrum. These include active microwave sensors, which

emit and receive reflected energy, such as radar imagers, scatterometers, and altimeters, and passive sensors, which simply receive radiation from the target area, such as microwave radiometers (36:xiii).

Little information is published, in unclassified sources, about the capabilities of Lacrosse. Yet, it can be assumed that technology is at its best with this recent addition to the space surveillance fleet. The French SPOT (*Systeme Probatoire d'Observation de la Terre*) satellites also have radar mapping capabilities and have ten-meter resolution (22:72). SPOT has been in use since 1986 (8:314), so the newer Lacrosse probably could do better than that. The USSR has admitted that their radar mapping satellites are capable of producing products with five-meter resolution for sale to other countries. If the Soviets are willing to sell five-meter resolution, they probably have better resolution for their military purposes. In terms of technology, the US can be said to have the same kind of resolution, so it can be hypothesized that Lacrosse is capable of approximately two- to three-meter resolution. This kind of resolution is not as good as the two-, or even six-inch resolution that the KH-11 and, presumably, the KH-12, are capable of. Nevertheless, the most important reason for using radar (microwave technology on the whole) is its ability to "see" through weather and at night (36:1). Future microwave sensing will be able to penetrate heavier weather, such as heavy rain showers and even ice clouds, and be able to detect metal composition (36:1).

Lacrosse, and the KH-11, have multispectral sensing capability also. Although not technically microwave technology, this type of sensor

electro-optically scans the target area over different frequencies[4], converts the "brightness" sensed into digital form, records the signals, and creates images in those frequencies for transmission to ground receiving stations (22:78). So, all of this technology gives a lot of flexibility to space reconnaissance.

Intelligence Dissemination. Space reconnaissance has witnessed several conflicts over the years, yet there has not been a major protracted conflict in which a sizable US force has been a part. Therefore, a proven wartime procedure for the dissemination of military intelligence has not been proven to exist. All that can be described is what happens in peacetime. Imagery from the Keyhole program (which, of course, the KH-11 and 12 are part) has gone to the National Photographic Interpretation Center (NPIC), in Washington, DC. This is the central processing and photo interpretation facility. All original imagery is stored here and duplicates are sent out to the users. In the case of intelligence requested by the Army, duplicate imagery is sent to the major military intelligence command, the 544 Strategic Intelligence Wing at Offutt AFB, Nebraska. From there, intelligence is sent to "the field"--Army Command Headquarters (8:208-211). Some multispectral imagery has been downlinked to receiving stations worldwide. Undoubtedly these products have taken a similar, if not an identical route, to the requestor, i.e., first to the CIA, then DOD, then finally to the requestor's chain of command. This system appears to have been set up for the benefit of peacetime civilian agencies.

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[4]Presumably, these frequencies are selectable for better intelligence gathering, such as infrared for night reconnaissance.

Although a capable national asset, space reconnaissance is currently ill-suited for Tac Recce. The limited number of satellites limits revisit time and the user interface through the CIA prevents timely intelligence. Existing space reconnaissance cannot meet the requirements of Tac Recce and should be augmented with a system that can meet the requirements.

Remote Sensing Technologies

Since the sensor is the most important component of any reconnaissance satellite, background information is needed on the technologies capable of remote sensing. Capabilities of sensors in the visible and infrared (IR) region of the electromagnetic spectrum is well documented. This paper will briefly review some of these types of sensors. This paper will also briefly cover the current capabilities and limitations of remote sensing in the microwave and millimeter-wave portion of the electromagnetic spectrum.

Visual/Infrared: Passive. Passive radiometry, receive only, in the visual/IR portion of the electromagnetic spectrum has been around for many years and has been well documented.[5] This technology includes the standard optical camera that is found in the RF-4C and the area of passive multispectral sensing.

Multispectral sensors break up the incoming electromagnetic energy, in whatever portion of the spectrum it is built for, into several bands and records those bands separately for analysis. The most recognizable sensor of this type is the Multispectral Scanner (MSS), and

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[5]See Dr. H.S. Chen's book, *Space Remote Sensing Systems*, for a review of the physics of this type of remote sensing.

the more advanced Thematic Mapper (TM), of the Landsat series of satellites. From a 705-km orbit, these sensors have a coverage swath of 185 km and a resolution of 79 m (MSS) or 30 m (TM). They have bands through the visual into the IR spectrum (0.45 - 2.35 micrometers). Other multispectral sensors, such as France's SPOT and NASA's Multispectral Linear Array (MLA), are basically improved versions of the Landsat sensors with better spectral and spatial resolutions (11:75-91).

Visual/Infrared: Active. A new active remote sensing system, energy transmitter and receiver, is called lidar (light detection and ranging). Such a sensor system combines a light source and a passive optical sensing system. In this system a pulsed laser illuminates a target area and the system's optics detect the backscatter laser radiation. The system consists of lasers, an optical system, detectors, electronics, and a recording system (11:171).

Presently there are two kinds of lidar systems. In the direct system the signal current is generated in direct proportion to received laser power. This system is simple, reliable, and relatively low cost. The other system is the heterodyne system, which measures the difference between a local oscillator and the received signal. This system has superior sensitivity and very high spectral resolution, but it is relatively complicated because it requires two lasers which need to be aligned.

An example of the characteristics of a lidar system is illustrated with a system containing a CO_2 laser. This type of laser is space-proven and poses no problems in lidar employment (11:172). A typical laser pulse length of 30 nsec corresponds to a lidar range resolution of less than 5 m (11:182). This kind of resolution comes at a price; the

laser requires 4000 watts of power (11:181). The system weighs 1990 kg without the power supply (11:182).

The lidar system appears to be very flexible. Different lasers could be used for different applications. Also, the system could be coupled with other remote sensing techniques such as synthetic aperture techniques. This synthetic aperture lidar system has resolutions in the range of 0.1-0.5 m (11:187).

Active systems do have a limitation. They are unable to perform multispectral imaging, which is important in material analysis and gives more intelligence than a simple photograph.

Microwave Remote Sensing. The basic principle in this type of remote sensing is that all matter radiates electromagnetic energy. This radiation is caused by the interaction between the atoms and molecules in the material. This material may also absorb and/or reflect other energy waves that may fall upon it (36:12). A microwave remote sensor, then, is a "highly sensitive receiver capable of measuring low levels of microwave radiation" (36:13).

Microwave remote sensing uses that portion of the spectrum in which the electromagnetic wavelength is between 1m to 1mm (0.3 to 300 GHz in frequency) (36:21). The use of microwaves in remote sensing exploits the electromagnetic wave properties in this region of the spectrum. The most important reason for using microwaves is because they have the ability to acquire usable reconnaissance at night and in the weather. Microwave energy can penetrate clouds, even ice clouds, which can completely obscure the ground from visual photography. Microwaves can also penetrate rain, which has more effect on microwaves than clouds do, up to a moderate level. Also, microwave sensing is

independent of the sun as a source of illumination (36:1). Another reason to use microwaves in remote sensing is because they can penetrate more deeply into vegetation than optical waves and even into the ground (36:2). Therefore, usable reconnaissance can be acquired through thick jungle canopies, and ground conditions, such as water content, can also be acquired. Finally, using microwaves in remote sensing gives the user more insight into the makeup of the target than visual or infrared sensing (36:3). Microwaves reveal not only the presence of an object but also what the object is made of (through multispectral comparisons or single frequencies against specific materials).

Space-based microwave remote sensors are generally divided into three types: imaging radars, altimeters, and scatterometers/spectrometers (13:5). These types of radars can be combined in order to meet the requirements of the users. Yet, for clarity, each type will be addressed separately.

Imaging radars are used in acquiring high-resolution pictures of the surface. They have been used in the study of geologic structures, ocean surface waves, polar ice cover, and land use patterns (13:5). Imaging radars are capable of giving three-dimensional and perspective views of the surface. Imaging radars are best suited for the reconnaissance role because the product is most like the picture that traditional visual photography would give (for user familiarity) and gives the kind of information that can be used in Tac Recce.

Altimeters are used for measuring the height of the surface. This is used in land and ocean topographic mapping, which can yield ocean

circulation data. This radar times a pulse from transmission to reception directly below the sensor, to determine satellite altitude (13:5-7).

Scatterometers/spectrometers measure "surface reflectivity as a function of frequency, polarization, and illumination direction of the sensing signal" (13:7). They are used to measure the "roughness" of the surface, and require high-accuracy calibration.

Passive Imaging Radars. Passive radars consist of only a receiver, and gather radiant electromagnetic energy which every object emits. The wavelength of an emitted wave is large, therefore the antenna needed to detect the wave would necessarily have to be large also. The diameter of a parabolic antenna for example is given by the equation:

$$D = \frac{\textit{sensor altitude} \times 1.2}{\textit{required spatial resolution}}$$

Therefore, for a sensor in low-earth orbit (LEO), in this case 300 km, with a required resolution of 5 m, an antenna diameter of 72 m is required, which is exceedingly large and difficult to place into orbit (11:157). Passive imaging radars are not well suited for the tactical reconnaissance role.

An example of a passive microwave sensor is the Nimbus 6 Electrically Scanning Microwave Radiometer (N6ESMR). From an 1100-km orbit it could achieve 20 m resolution in the 37 GHz frequency (11:163).

Active Imaging Radars. Active radars consist of both a receiver and a transmitter of electromagnetic energy. Most active imaging radars used for remote sensing are side-looking airborne radars

(SLAR) (36:42). The way SLARs work is best summarized by the German Aerospace Research Establishment (DFVLR) as follows:

> A short pulse is transmitted through the antenna that faces to one side of the aircraft. The reflection depends on the ground surface, the roughness of the ground and the distance to the antenna and represents the radar cross section. The smallest ground area that can be distinguished is called the resolution cell which depends on the length of the pulse and the beam width of the antenna in the along-track direction. The time-dependent received signal gives the information of the pulse echo in the cross-track direction and is processed to give one radar image line. The processing for the next image line starts when the aircraft has moved a certain distance. Repeating this process enables a complete image to be produced. (39:7)

The sensor's antenna emits a horizontally narrow, vertically wide beam at the ground (36:43).

SLARs are divided into real-aperture and synthetic-aperture systems. Real-aperture radars depend upon the actual antenna beamwidth for its imaging. This technique gives a resolution which is linearly proportional to the range to the target (14:193).

Synthetic-aperture radars, on the other hand, operate on the principle that a target stays in sight of the sensor for a period of time and is observed several times during a sensor pass. This allows for computer signal processing techniques to be used in order to achieve a very narrow beamwidth (compared to real-aperture radars), in the along-track direction, and therefore smaller resolutions (36:45). Figure 1 graphically illustrates the advantage of synthetic-aperture over real-aperture radar in terms of along-track resolution. Following custom, in this paper the term "SLAR" will refer to real-aperture systems, while the term "SAR" will refer to synthetic-aperture systems.

SLAR. SLARs are usually not used in high-resolution imaging because of the inherent limitations due to fixed antenna beam-

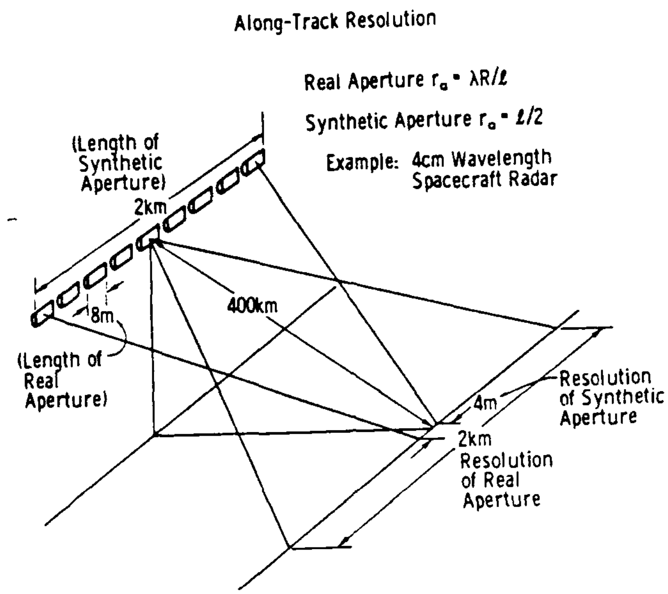

Figure 1. Illustration of Advantage of Synthetic Over Real-Aperture Radar (36:48)

width. They are used, though, for scatterometry and altimetry (14:193).

A concept has been proposed to use real-aperture systems for imaging. This concept puts a series of small satellites, which are spaced about one to five kilometers apart, in low-earth orbit, typically 600 kilometers in altitude. The system is called a distributed array radar (DAR) (30:17). The concept will allow the system to have "good visibility through foliage, excellent clutter rejection, ability to detect relatively small targets, SAR processing capability, and extremely good moving target indication [MTI] capability" (30:17). These satellites are identical and are essentially tied together to form one very large antenna. It can be seen that this system would be capable of very narrow beams, which gives the system its excellent MTI capability (less than 5 knots radial speed can be detected) (30:19). This system requires a substan-

tial ground facility for data processing and correlation. Yet, the DAR system is capable of fully functioning even if several of its satellites are disabled, through hostile acts or malfunction (30:18). This makes the system very flexible and survivable in a wartime scenario.

SAR. The newer type of side-looking radars is the synthetic-aperture radar (SAR). This radar can achieve resolutions many times better than the older technology SLARs. Along-track resolution is given by the equation:

$$r = \frac{L}{2}$$

where r is resolution and L is the length of the sensor's antenna. So, the shorter the antenna, the finer the resolution. This resolution, also, does not depend upon the range to the target (36:47; 14:204). This implies that high resolutions can be achieved with smaller and lighter systems.

A characteristic of any imaging radar system is the cross-track resolution. Theoretically, this is given by the equation:

$$r = \frac{c}{2\,B\,\sin\theta}$$

where r is resolution, c is the speed of light, B is the system's signal bandwidth, and θ is the system's look angle from nadir (11:191). This implies that finer resolutions require larger bandwidths.

Another characteristic of side-looking radars is the swath width, or cross-track ground coverage. Typically, swath widths are about 100

km, but can be increased to about 400 km through mechanically stepping or phase shifting the antenna to achieve different selection angles (11:192).

SAR systems are not without problems. One major problem in real-time gathering of information is processing time. For example, it takes a SAR sensor 13 sec at 7.5 km/sec spacecraft velocity to cover one 100x100 km frame, yet, it takes 2.5 min/frame to process the data. Also, at a 110 Mbps (million bits per second) per channel data rate, a multichannel transmitter will need data compression in order to achieve its mission (11:193). Another problem is power. All active radar sensors are characterized by large transmitter power requirements. Typically, 1000 watts of power are needed to run a SAR system (11:194).

Millimeter-Wave Radar (28:285-287). Millimeter-wave technology is fast maturing. This remote sensing technology uses electromagnetic energy with wavelengths of about 500 micrometers to 1 centimeter. This technology has advantages and disadvantages over microwave remote sensing.

One advantage is that more information can be gathered about the make-up of a target because this technology uses shorter wavelength energies, which result in narrower beamwidths and smaller antenna apertures. This reduces the scattering of larger wavelengths and can image at the microscopic level. These smaller apertures lead to another advantage of reduced physical size of the sensor. Finally, millimeter waves have extremely wide frequency bandwidths, in fact, the entire microwave frequency range can be contained in one millimeter-wave band. This leads to "greater resolution and sensitivity for radar applications, larger data transmission rates for communications, reduced

interference between mutual users of the band, and improved security because of the large space in which to hide" (28:286).

Disadvantages to millimeter-wave radars are few but significant for space-based remote sensing. One disadvantage is limited range. This is due to the smaller aperture which limits the amount of energy that can be collected. Since millimeter waves are smaller, there is more interaction with the atmosphere. This accounts for another disadvantage in that atmospheric attenuation is greater, further reducing range, and all-weather operation is prevented.

In summary, the background information on resolution will help in analyzing reconnaissance sensors. Information on the RF-4C aids in understanding the current Tac Recce system, which provides insight into any proposed satellite system. Also, background on current space-based surveillance systems establishes the basis from which a new reconnaissance system can emerge. Finally, an overview of some remote sensing technologies gives an appreciation of the limitations and capabilities of a space-based reconnaissance system.

III. *Systematic Systems Approach*

In Athey's "Systematic Systems Approach," criteria are ranked and weighed, desired and expected performance are determined, and finally alternatives are ranked. Before these steps are taken, system requirements, constraints, and system component options need to be explained.

Requirements

User requirements define the space in which a viable tactical satellite must fall. If a system cannot fulfill the needs of the user, then the system should not be acquired. The following requirements are derived from Frank Moon, Army Space Institute, and Dr. Shelba Proffitt, Advanced Technology Directorate, US Army Strategic Defense Command. A Tac Recce system should be:

1) Under direct control of field commander

   This requirement implies that targeting is best served by those in the field, which allows for rapid changes in the order of battle.

2) All-weather, day/night coverage

   This implies that the system must be very flexible in meeting the users needs.

3) Wide-area coverage with high resolution (<3 meters)

   This requirement appears to be incongruent. It is asking for a system that can acquire a lot of coverage, yet at the same time have high resolution. Yet, since the KH-9, both wide area and high resolution has been achieved onboard

satellites. The challenge here is to developed a tactical satellite that can accomplish both.

4) Real-time data transmission

This requires a system to transmit data directly to the user in the field, with only processing time delay. This implies that there is onboard processing or processing units deployed in the field.

5) Deep battlefield surveillance

This requires the tactical satellite system to be capable of detection, identification, and location of targets. It equates to targeting data and battle damage assessment (BDA) for retargeting and optimum use of resources, such as Air Force bomber strikes.

6) Launch versatility

This requirement is asking for a flexible, mobile or transportable, launch system. This also requires a launch on demand aspect.

7) Survivability

This requires the launch facilities, ground receiving stations, and the satellite, to include its basing, to have aspects that make those components of the overall system survivable in an armed conflict.

8) Frequency of coverage that meets the needs of the field commander

This requires the system to have revisit times of between 2-12 hours. Yet, it must be noted that the Army is willing to accept a maximum constant revisit time of 8 hours. Revisit

times do not pertain to satellites in geostationary orbits, which have continuous target coverage.

Constraints

Major constraints in solving the problem are those conditions or restrictions that must be met in order for a system to be considered feasible. The following constraints are as described by Col Noel S. Miyamasu, Director of Special Projects, Electronic Combat and Reconnaissance SPO, US Air Force Systems Command.

1) Three-year development cycle

   This constraint implies not only that the system and technology is time dependent (long lead times prevent the most current technology from being utilized), but that off-the-shelf (proven) technology, or at least technology that is achievable within a short period of time, must be used.

2) Present, or near future, capabilities of satellite data transmission must be met

   This implies that whatever system is deployed it should be able to utilize current space and ground assets, such as relay satellites and communication vans, and not require a whole new set of support assets of its own.

System Options

Electrical Power Sources. When evaluating which power source to use on a satellite, weight, reliability, capability, and cost must be taken into account. Further, in a military tactical satellite, survivability must also be evaluated. The following is a list of the most promising power systems by type.

Electrochemical. Electrochemical devices are energy storage devices which employ a chemical reaction in order to produce electrical power. Considered survivable in that only a kinetic energy weapon would be able to disrupt power output.

Primary Cell Batteries (1:Chapt 4,3). The primary cell battery is a one-cycle (one-time use) device that converts chemical energy directly into electrical energy. Energy density is too low and is therefore good only for mission durations shorter than a few months. It is not feasible on a tactical satellite whose lifetime is 2-3 years.

Secondary Cell Batteries. These batteries are a rechargeable device. They have a lower energy density than primary cells, typically 12.9-16.6 W-hr/lb (watt-hour per pound) for a nickel-cadmium (NiCd) battery. Secondary cell batteries are excellent as the backup for solar arrays during eclipse periods, yet often are the heaviest component of power system (1:Chapt4,3).

NiCd (Nickel-Cadmium). This battery is the type most often used in space applications. It is reliable and a lot is known about the system (10:572).

NiH_2 (Nickel-Hydrogen). This battery has a higher energy density (19.0 W-hr/lb), is lighter (by 15%), and has a longer life cycle than a NiCd battery, but it is 2.5 times larger in volume. It has good reliability and is proven technology. It is considered a good alternative to the NiCd battery (10:572).

HEDRB (High-Energy-Density Rechargeable Battery) (10:572). This is an advanced technology battery that produces as much energy as a standard battery with considerably less weight. For example, for a 10-kW eclipse power demand capability, a NiCd

battery would weigh approximately 1400 lbs, yet a HEDRB would only weigh 300 lbs. This battery would employ either a lithium alloy-metal sulfide (Li-alloy/MS) or a sodium-sulfur (NaS) chemical reaction to produce the energy. This type of battery will be available by 1993. This type of battery would be useful in reducing the size and weight of a tactical satellite. Although not space proven and slightly more costly to produce (only because it is not mass produced at this time), it is the best battery under consideration.

Fuel Cells. Separately stored fuel and oxidizer are combined to produce the chemical reaction needed to produce electrical energy in this type of power source. They have longer durations than primary cell batteries, yet they take up more space (1:Chapt 4,4). They are not feasible in a tactical satellite because of size restrictions and are limited to one-time use.

Chemical-Dynamic. This electrical power source uses the chemical reaction of fuel combustion (either fuel/oxidizer or reactant/catalyst) to drive a mechanical (dynamic) energy converter (such as a turbine generator) in order to produce power. These are high-energy systems, yet they also have high fuel consumption rates (1:Chapt 4,5). Chemical-dynamic systems are not feasible for tactical satellites because of the fuel storage volume needed for the mission duration.

Solar. Solar power systems use the sun's energy to produce electrical energy. These types of systems are not survivable in a military environment because solar collectors are exposed and are very susceptible to attack. Solar collectors are easily damaged by ASAT, laser, or kinetic energy weapons. Even though they are long-lived, these types of power systems degrade over time due to radiation in the

space environment. Yet, a tactical satellite with a mission duration of less than 3 years and in a low-earth orbit (out of the Van Allen radiation belts) would not be noticeably degraded.

Solar Cell (10:569). The solar cell is rugged, relatively reliable, available, and flight proven. It is the power system (coupled with batteries) that is the most widely used today. They are heavy, require a great deal of area, and must be pointed at the sun (which adds subsystems, for tracking the sun, aligning the arrays, and battery conditioning, which in turn adds complexity and weight). Typical solar/battery systems produce approximately 10 watts/ft^2, weigh about 1000 kg/kW, and cost about $250/watt. This system is usable in a tactical satellite.

Solar-Dynamic. This system focuses the sun's radiation to heat a medium, which in turn would do work, which is converted into electrical energy. This system would be able to produce many kilowatts of electricity. Yet, it is too big and too heavy for unmanned applications (1:Chapt4,7).

Nuclear (2:ix-x,244-246). Nuclear power systems rely upon released radiation energy in order to heat a medium, which in turn does work which is converted into electrical energy, or converts heat energy directly into electrical energy. These systems have long lifetimes, are compact in size, have low mass, can be operated in hostile environments (such as in the Van Allen radiation belt), do not require a solar source, have high system reliabilities, are autonomous, and produce high power. Emphasis on design of these systems has been on safety. This is evident in NASA's design requirements which "ensure that the levels of radioactivity and the probability of nuclear fuel release will not provide

any significant risk to the earth's population or to the terrestrial environment" (2:x). Nevertheless, the use of nuclear materials in satellites is not politically acceptable at this time. Even though the technology is not new, the costs to manufacture nuclear systems are still quite high. These systems are very survivable in a military environment. There is no dependence on external collectors which could be damaged and the required shielding also ensures that power would be available after a partially successful attack. These systems are comparable in weight with typical solar array/battery systems.

Reactor. A nuclear reactor uses energy released through the fission of the fuel in order to heat a fluid medium which does mechanical work which is converted into electrical energy. Reactor systems are capable of large quantities of energy (up to 300 kW). These levels of energy are not required in a tactical satellite.

Radioisotopic-Thermoelectric. Radioisotope decay is a way to produce nuclear energy. The predictable decay of an unstable element (typically Pu-238) gives off the radiation required to heat a fluid medium. This type of power system requires only shielding sufficient for containment of the fuel against accidents, which makes it much lighter than other types of nuclear power sources. It is also less dangerous than other nuclear systems, because it is more of a passive system. Out of 19 satellites with nuclear fuel launched since 1964, the US has had only 2 accidents. In both cases there weren't any problems with the containment systems. This system is proven in space, competitive in weight with solar cells, but is more costly. The cost of a typical system is about $10,000-50,000/watt. These systems can produce between 500 watts and 10 kilowatts, in standard Brayton, Sterling, or

Organic Rankine cycle engines. Of the space-proven power sources, the radioisotope-thermoelectric option is the best for a tactical satellite.

Radioisotope-Thermionic (15). This technology provides electrical power by placing a thermionic device next to the radioisotope. The thermionic device converts heat energy directly into electrical energy. This type of power system would be lighter and smaller than one that does mechanical work. This system has been successfully demonstrated to produce up to 10 kW of electricity in ground tests. Although unproven in the US, the Soviets have launched a satellite containing this type of power source. If developed within the next few years, this type of power source is better suited for a tactical satellite than the radioisotope-thermoelectric power source.

Basing Options (18). Parameters for basing options include the size of the constellation, the disposition of spares, and orbit parameters such as height, eccentricity, and inclination. In terms of size of the constellation, there could be many small satellites or a few large satellites. The options concerning spares are on-orbit or ground spares. Options for orbit parameters include low-earth or high-geosynchronous orbit, zero or high eccentricity, and 0-180° inclination.

One option in constellation size is to have a large number of small, simple satellites. This would meet the system requirement of survivability through redundancy. It would also lower the cost per satellite through mass production. The system would have worldwide, near-continuous coverage. The system would have good reliability through simplicity. The system would also be responsive in time because of small revisit times and, coupled with the Pegasus booster, have a responsive launch, meeting two system requirements.

A large number of small satellites has disadvantages, too. The system would have less capability because the small simple satellites cannot put a lot of different sensors on target at the same time. The total system may be more expensive than a single large satellite (depending upon the number of satellites in the constellation). More command and control would be needed for the entire constellation. Finally, more data would need to be processed.

Another option in constellation size would be to have large complex satellites. The constellation would be smaller than a constellation of small satellites because of fiscal restraints. Advantages to this approach include being more capable. The satellite would be able to do more tasks because there could be more systems/sensors onboard. There would also be more power available for the satellite's systems because the booster that would have to lift the satellite would also be able to carry large solar arrays or large nuclear power systems.

Large complex satellites also have disadvantages. Loss of a complex satellite would represent a single point failure in the overall system. Each satellite would be expensive and would be "one of a kind." The satellite could be out of position in crisis. Finally, there could be more conflicts over user and targeting priorities.

The best option, in terms of number of satellites in the constellation, for a Tac Recce satellite system is to have a large number of small, simple satellites. The larger constellation would ensure that the requirement of short target revisit times is met. A satellite system solely concerned with Tac Recce would not need complex satellites, therefore small, simple satellites can accomplish the mission for less cost than large, complex satellites. In addition, the requirement of survivability is

met with a large constellation. (Disabling one or two satellites in the constellation would not disable the entire system.)

Besides constellation size, another basing option is spacecraft spare/replacement disposition. One option within this category is that of on-orbit spares. This option would enable quicker replacement of damaged/destroyed satellites. Also, satellite status could be monitored so that controllers would be able to know if it was functioning properly.

The disadvantages with this option include the satellite being out of position when needed, therefore more maneuvering fuel would be required. Also, this option could make the system more expensive if satellites needed to be replaced over time.

The other option concerning the disposition of spares would be launch-on-demand/ground spares. Under this option satellites could be stockpiled and/or updated on the ground. They could also be placed into holes in the constellation directly.

With this option, though, the controllers would not be sure that the satellite would work in space until after it got there, which could be too late. Also, there could be delays in launching the satellites into orbit depending upon the booster used (days to months to years) and there must be ground facilities to maintain the satellites in a launch-on-demand status.

In order to ensure that the requirement of short revisit times is met, disabled satellites must be replaced as soon as possible. The option of having on-orbit spares is the best at accomplishing this replacement. These spares would be known to be operational and need only to be maneuvered into position.

The last area of concern in basing options is orbital parameters, which include height, eccentricity, and inclination. The height of the orbit is the first aspect that will be analyzed. The satellite could be placed in low-earth orbit (LEO). A sensor in LEO would get better resolution than at a higher orbit. A satellite in LEO would produce shorter orbital periods which will usually provide shorter target revisit times. Another advantage of LEO is that the current and near-future tactical launch systems are able to place satellites of reasonable size into LEO, while only large, costly boosters can place satellites into higher orbits.

Placing satellites in LEO has disadvantages. Satellite life would normally be shorter due to more atmospheric drag requiring more maneuvering. Satellites in LEO would be easier to attack from ground lasers (less distance would require less laser power) and anti-satellite (ASAT) weapons (less time to react and maneuver the target satellite in case of an ASAT launch).

Another orbit to consider is geostationary orbit (GEO). A satellite in GEO has the advantage of being able to constantly monitor large target areas. A satellite in GEO is also less likely to encounter hostile attack from direct-assent ASAT weapons. A system using satellites in GEO would require fewer satellites in order to achieve global coverage. In addition, the satellites in GEO tend to have longer lifetimes than in LEO.

Satellites in GEO also have disadvantages. In order to achieve usable resolution from GEO, larger, more costly optics are required for the sensor. Currently, only launch systems that are large, expensive,

and require long lead times are available to place reconnaissance satellites into GEO.

The best orbit height for a Tac Recce satellite system is LEO. A constellation of satellites in LEO meets the requirements of high resolution and short target revisit times. Satellites can also be placed into LEO using small, tactical boosters fulfilling another system requirement.

Orbit eccentricity is another parameter that should be analyzed in determining the best orbit option for a Tac Recce system. One option is to have a circular orbit (zero eccentricity). This orbit would allow the satellite to have constant scale and resolution over its entire orbit. In this orbit, a satellite need not be repositioned or have to expend fuel in order to change its orbit if targets in different parts of the world required high resolution. At the proper geosynchronous orbit altitude and zero inclination, a satellite in a circular orbit would have a stationary ground track ensuring continuous target coverage. Yet, a major disadvantage with a satellite in such an orbit is that the earth's polar regions could not have continuous monitoring.

Another option for orbit eccentricity is a highly elliptical orbit, such as a Molniya orbit. This type of orbit allows for extended continuous coverage of polar targets, with the proper inclination. Yet, such a highly elliptical orbit prevents portions of the orbit from being usable for reconnaissance because the sensor would be moving too fast when at perigee. In addition, a satellite in a Molniya orbit would require more energy to attain its orbit, therefore a large powerful booster would be required to place the satellite in orbit. Also, distance to the target area is a problem, as with GEO.

The best orbit eccentricity for a Tac Recce satellite is zero, or a circular orbit. This orbit would ensure consistent worldwide monitoring and, coupled with a LEO, could be placed into orbit with a small tactical booster.

The last parameter that will be analyzed for orbit determination is inclination. The satellite could be in a sun-synchronous orbit so that its solar panels are constantly in sunlight and/or the target area is under the same lighting conditions on subsequent daily passes. The satellite could be in a polar orbit so that worldwide coverage is maximized. The satellite could also be in a 0°-inclination orbit (equatorial), coupled with the required geosynchronous altitude, so that the satellite remains over the same spot on the earth for constant target coverage.

There are also disadvantages to these inclinations. Since a satellite in a sun-synchronous orbit would pass over a target at exactly the same time daily, preparations could be taken for counterintelligence/misrepresentation at the time the sensor is overhead (assuming a single satellite constellation). Also, there is not going to be much military action (for Tac Recce to monitor) in the polar ice caps, so a satellite in a 90°-inclination orbit would not be used most efficiently. Finally, a satellite in an equatorial orbit would not have the benefit of passing over targets in the middle latitudes where most of the world's population and potential areas of conflict are located.

The best inclination for Tac Recce satellite is a near-polar inclination (not more than 70°). This type of inclination ensures that all major target areas, where potential conflicts may occur, are monitored. This is more important for a system that is monitoring crises worldwide prior to

hostilities, yet has the flexibility to insert sensors into the best inclination for the situation and intelligence required.

Summarizing, in order to fulfill the requirements of a Tac Recce satellite system, the best basing options are a large constellation of small, inexpensive satellites in near-polar, low-earth orbits with on-orbit spares. A constellation meets the requirements of short revisit times and survivability. Small, inexpensive satellites are fiscally responsible, because a large constellation of large, complex satellites would be cost prohibitive. In addition, small satellites could still achieve the required resolution with the proper sensor. The satellite would be in a LEO of about 300 km which would give good resolution yet not low enough to be adversely affected by the atmosphere. On-orbit spares increase survivability and ensure that frequency of coverage has minimum interruptions. These satellites should all be in the same plane so that, in case of satellite repositioning, maneuvering fuel is minimized, therefore maintaining as small a satellite as possible.

Boosters. Of all of the boosters, present and proposed, that could place a Tac Recce satellite into orbit, only two boosters are capable of meeting all of the system requirements and constraints stated at the beginning of this chapter. Specifically, the Tac Recce satellite system would require a booster that is survivable, have a relatively short launch preparation time, and will be available within three years. These two boosters are the Taurus launch system and the Pegasus launch system.

The Taurus booster is a proposed mobile launch vehicle that is a variant of the MX missile. This booster will be deployed in the early 1990s and meets all the stated requirements and constraints. The

Taurus is transportable for survivability. It can lift medium-sized/ weight satellites into orbit (1000 lbs into LEO). Yet, it has a long lead time (1-2 months) required for each launch. It is apt to be constrained by road conditions and launch trajectories over inland populated areas, which could be a problem. It is also the more expensive option ($15 million).

The Pegasus has a quick-launch capability (72 hours). It costs only $6.3 million per launch. Since it is an air-launched system, it can place its payload into any inclination. Like the Taurus, it is also survivable because it is not tied to any launch pad. Unlike the Taurus, it is not hampered by terrain or road conditions, and, when launched over water, launch trajectory is not a factor. Its major disadvantage, though, is that it can only carry small satellites into LEO (about 600-700 lbs).

The best booster to place a Tac Recce satellite into its orbit is the Pegasus launch system. It is more flexible and less costly than the Taurus launch system. Nevertheless, if the size of the Tac Recce satellite cannot be reduced enough to be able to utilize the Pegasus, then the Taurus would have to be used, yet this does not represent a major reduction in capability.

Final Alternatives

The final alternatives represent three systems from a continuum that falls within the system constraints and meet, in varying degrees, the system requirements. They will be separated in perceived threat scenarios and cost. The final alternatives will be listed as complete systems. The first alternative will describe all of its important compo-

nents. The system components are the satellite (which is broken down into six satellite subsystems), the launch vehicle (and options if any), basing, mission control, and ground equipment. The subsequent alternatives will only address those portions that are different from the first.

System 1. This tactical reconnaissance satellite system will employ a constellation of small satellites carrying single sensors launched by the Pegasus booster into LEO and theater-based ground equipment.

This system assumes supporting a rapid-deployed force anywhere in the globe. Further, time to hostilities is short. This also assumes that the survivability of the system depends upon the survivability of each component and that advanced anti-satellite weapons could be employed against the system.

Satellite. The satellite is broken down into six subsystems which are structure; attitude and velocity control; electrical power; thermal control; telemetry, tracking, and commanding; and payload.

Structure. The structure will feature a modular bus supporting multiple payloads, orbits, and missions. It will support modular payloads. This will reduce costs through production of a generic satellite with minor modifications for different payloads. The structure is fully compatible with the Pegasus launch vehicle. The structure, as well as every other component of the system, will be constructed with proven high-strength, low-cost materials. The satellite will weigh 670 lbs and will support up to 250 lbs of sensor payload (21).

Attitude and Velocity Control. The satellite will have 3-axis stabilization using reaction wheel control. This is fairly standard and is proven off-the-shelf technology, thereby decreasing acquisition time and cost. It will feature autonomous navigation and control. It

will utilize GPS data as a primary source of position data. It will also have a Honeywell-developed ring laser gyro inertial measurement unit (which is no wider than a quarter) updated by GPS in case of lost contact or temporary receiver failures (3:77). This will cut down on the weight and space required for horizon and sun sensors. This will make this portion of the satellite more autonomous and survivable because the satellite will not have light sensitive receivers that could be affected by a laser attack. This will cut down on the overall weight of the space-craft because GPS receivers have become very small and lightweight. It will have 10 small ion propulsion thrusters for control and momentum management cutting down on the mass of the typical hydrazine fuel needed for station keeping (21).

Electrical Power. Power will be supplied by radioisotope decay of Pu-238, whose emitted radiation energy is converted to electricity. This power supply subsystem is safe, weighs about as much as a solar array/battery power system, including the requisite shielding, and makes the satellite a much more survivable component of the system. Survivability comes from the lack of solar arrays vulnerable to attack. The system, depending upon the requirements of the sensor, will contain enough fuel to produce between .5 and 1.5 kilowatts of power.[6] In order to cut down on weight and volume, a thermionic direct energy conversion system will be used instead of the usual power cycle/generator system, such as the Brayton, Rankine, and Sterling cycles.

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[6]These power requirements are estimates and will vary with an actual system, yet they represent the power required for average satellites with these type sensors and other equipment.

Thermal Control. The satellite will use passive thermal control mechanisms. It will have blankets for those units that require insulation and radiators with heat pipes to release excess heat from the power source.

Telemetry, Tracking, and Commanding. This subsystem will be compatible with the Air Force Satellite Control Network (AFSCN) facilities and the Space Ground Link System (SGLS). The system must be able to support satellite housekeeping. It must be able to uplink commands (such as injection, initialization, power conditioning (if necessary) and orbit adjustment) and ephemeris determination. To do this, the satellite will have 2 S-band antennas (1 kbps - 1 Mbps) for housekeeping and some command instructions from the Air Force maintainers (21).

The system must also ensure that the users are supported. It must be able to downlink sensor data to users in a timely manner and in an easy to use form. Further, users must be able to select the desired operating mode and pointing direction. To accomplish this the subsystem will include a MIST[7] compatible X-band downlink (a 2' steerable dish). This will enable the user, utilizing a 6-ft antenna, to receive up to 274 Mbps of data. It will also have a MIST compatible X-band uplink (a omnidirection antenna) for user in-theater control (it could also support housekeeping commands if necessary) (21). This makes the satellite compatible with existing and near future ground and

[7]MIST (Modular Interoperable Surface Terminal) is a Army C^3 van. It is currently employed and is compatible with common user ground networks, such as AUTOVON and AUTODIN.

space assets. The subsystem will also include encryptors and decryptors that are necessary and compatible with existing military equipment.

Payload. There are two different payloads that can be on each satellite. They are the multispectral imager and the synthetic aperture radar (SAR).[1]

The multispectral imager was selected because of its flexibility and familiarity. This sensor meets the system requirements of flexible, wide-area coverage with high resolution and deep battlefield surveillance. The separate bands of a multispectral imager can provide different information on a target depending upon the user's desires. In addition, this type of sensor is widely used, space proven, reliable, and available.

The imager will record images in the visual to the near infrared region of the electromagnetic spectrum (.4 μm - 12.5 μm). This will give the system limited weather, night, and camouflage capabilities. The imager will utilize a pushbroom scanning process with electronically scanned detector arrays. In a pushbroom scanner, a line array detector at the focal plane of the imaging optics is lined up so that the projected FOV is perpendicular to the direction of movement and a single line array is imaged at a time. The movement of the satellite provides along-track coverage. The sensor will also have a 50:1 telescoping feature in order to accomplish both wide-area and high-resolution

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[1]The sensors described here are a combination of existing technology and proposed sensors from McDonnell and Lockheed. These sensors are possible and feasible, yet capabilities are approximate and final configurations may change. These sensors represent the minimum required to meet the mission requirements, yet other more advanced sensors could be substituted.

reconnaissance.[9] In order to meet the system requirement of wide-area surveillance, the sensor will have a swath width of approximately 100 km; this also happens to be the most prevalent sweep angle of a push-broom scanning sensor (15°).

The frequencies will be divided into seven spectral bands[10] by a series of beamsplitters. Bands allow for frequency analysis in determining material composition. Each band requires its own CCD pixel array in the focal plane of the sensor.

The instantaneous, and total, field-of-view of a sensor is determined by the number of pixels and the pixel size in the focal plane (32:109). In order to meet the requirement of determining vehicles in an image, in the narrow FOV mode, the intelligence community requires a NIIR (National Imagery Interpretability Rating) category 5 (.75 - 1.2 meter resolution). This allows for the determination of the general class of tanks. With this kind of resolution, strength and location of heavy ground forces can be determined, as well as reconnaissance, such as BDA (battle damage assessment), for other potential users such as the Air Force.

In order to get approximately one-meter ground resolution from a 300-km orbit, the IFOV (instantaneous field-of-view) has to be 3.3 µrad.

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[9]This telescoping capability has already been demonstrated and is a feasible feature of this sensor (27).

[10]Seven spectral bands is prevalent in the industry. With more bands, spectroscopy, a composition analysis methodology, is enhanced. Yet, more bands require more CCD pixel arrays, which, in turn, produce more data that must be processed and transmitted via more capable systems. Seven bands seems to be a good compromise between information and data overload.

With an aperture FOV of 0.75° and a scan rate of two scans per second,[11] the focal plane needs to have eighteen (arranged in two rows of nine) 2000 X 2000 pixel arrays.[12] At the standard 8 bits per pixel, this would equate to a 1.152 Gbps data transmission rate per band. Over seven bands, there will be 8.064 Gbps acquired. This data transmission rate far exceeds existing capabilities, therefore data compression is required. With proper data processing on the ground, a transmission with 50% data compression can produce a frame that is 100% of the original (17:94). Fifty percent compression would still not allow real-time data transmission even at the upper limit of existing capabilities (280 Mbps). Higher amounts of data reduction (up to 90%) are being developed and will be required for this system when available. To reduce data further, the system will only detect and transmit one or two spectral bands worth of data depending upon the target. All seven bands are not needed in most reconnaissance. Nevertheless, onboard data storage prior to transmission is necessary for those cases where one or two bands of data is not enough. This means that real-time data transmission is impossible. The users must accept near real-time with a delay of approximately 30 minutes. Furthermore, relay satellites may be required to transmit data to the user when the satellite is out of direct

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[11]This is feasible because the prevalent FOV in the remote-sensing industry is approximately 1° and existing weather satellites have the two scans/sec capability. This FOV and scan rate ensures that the sensor does not have any holidays (gaps in continuous coverage) because of the satellite velocity of approximately 7.7 km/sec.

[12]The 2000 pixel multi-anode microchannel array has been demonstrated by Ball Industries, with impressive results, such as real-time image motion compensation and good nighttime target resolution (down to 1 photon per pixel, with digital enhancement, equates to finding tanks in the shadows of a moonlit night) (6:296). Further, Honeywell has developed 2048 x 2048 13 μm pixel arrays.

contact because of the large amount of data and the short amount of time that the user and satellite are in direct contact (8-9 minutes).

Self-structured magnetic bubbles will be used as the needed buffer (33:98). A standard 1.6 micron bubble system has a memory capacity of 10^{10} bits, can read/write up to 30 Mbps, has a maximum power requirement of only 40 watts, and has a bit error rate of 10^{-8} (uncorrected), all feasible spacecraft configurations. A series of modules containing the bubbles can be set up to handle any storage requirement depending upon the sensor design. This design is lightweight, approximately 20 kg in this scenario.

The SAR will be the other sensor payload. It will be used for night and through-the-weather coverage, in addition to limited material composition analysis, such as ground water determination. The radar will operate at a frequency of 15 GHz (Ku band), utilizing a 2-meter diameter antenna. This will consume about 1000 watts of power to operate, yet a nuclear power source will be able to handle the power requirement.

This selection of radar frequency is, of course, flexible. The selection of 15 GHz represents a compromise between transmission losses through the atmosphere, rain, clouds, and power demands (where higher frequencies require more power). Figure 2 shows the relationship between the percent of transmission of microwave energy and the atmosphere, while Figure 3 and 4 show the percentage of transmission through rain and clouds, respectively.

SARs do not use pushbroom scanning techniques, so this sensor will use 9 (3 by 3) 2000 x 2000 pixel arrays. Again, in order to get one meter ground resolution, the sensor needs 3.3 μrad IFOV. The sensor's

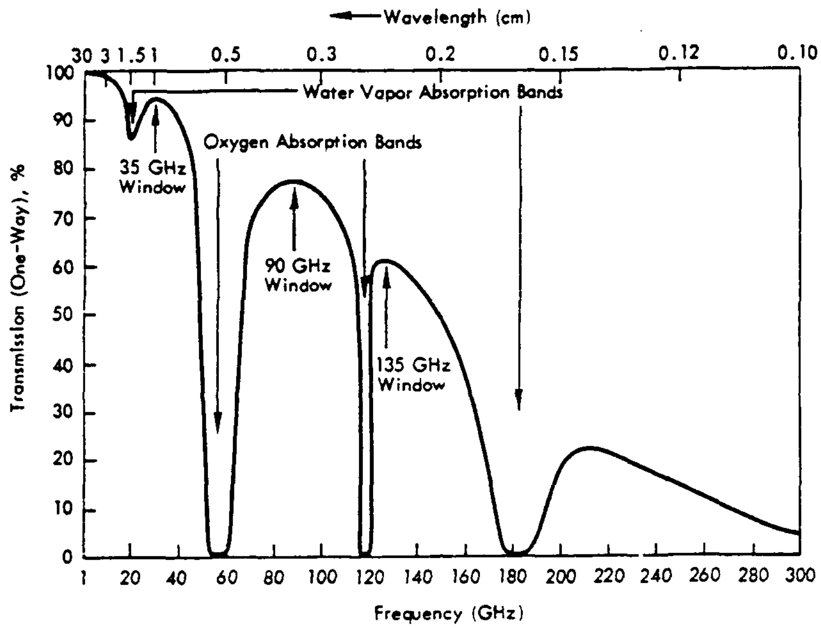

Figure 2. Percentage Transmission Through the Atmosphere Under Clear-Sky Conditions (36:20)

coverage is only 25 km^2, so this sensor will only be used for special targets. Pointing accuracy is very important for this sensor, yet existing capabilities of 2/100th of a degree is acceptable.

Data storage is not as big as a problem with this sensor. Storage will still be handled in the same manner as in the imager, yet not as many magnetic bubbles are needed.

Launch Vehicle. The Pegasus air launch booster will be the launch vehicle. The Pegasus is a successfully demonstrated booster with a 72-hour launch capability. It is the most flexible and survivable booster, because it does not have fixed launch pads and it has the ability to directly insert a satellite into any orbit inclination.

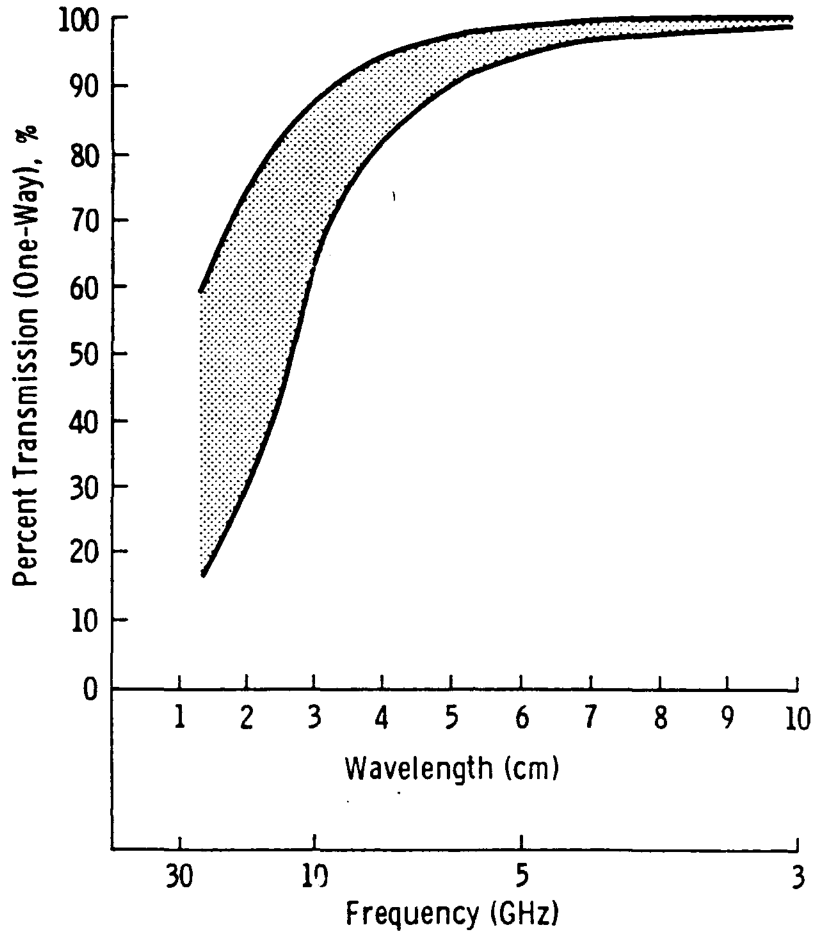

Figure 3. Effect of Rain on Transmission from Space to Ground (36:3)

Basing. The system will employ four satellites in orbits separated by 45° of longitude.[11] The satellites will be in a near-polar inclination (approxiamately 70°) at an altitude of 300 km and a period of 90 minutes. This will give the system target revisit every three hours. This represents an initial basing which will be used for the training and

[11]Basing for this system is flexible. In times of crisis, the Pegasus booster can insert extra satellites into LEO at any inclination. The setup described here will be used in the early stages of a conflict (before more satellites can be placed into the proper orbit) and for training (MCC and field).

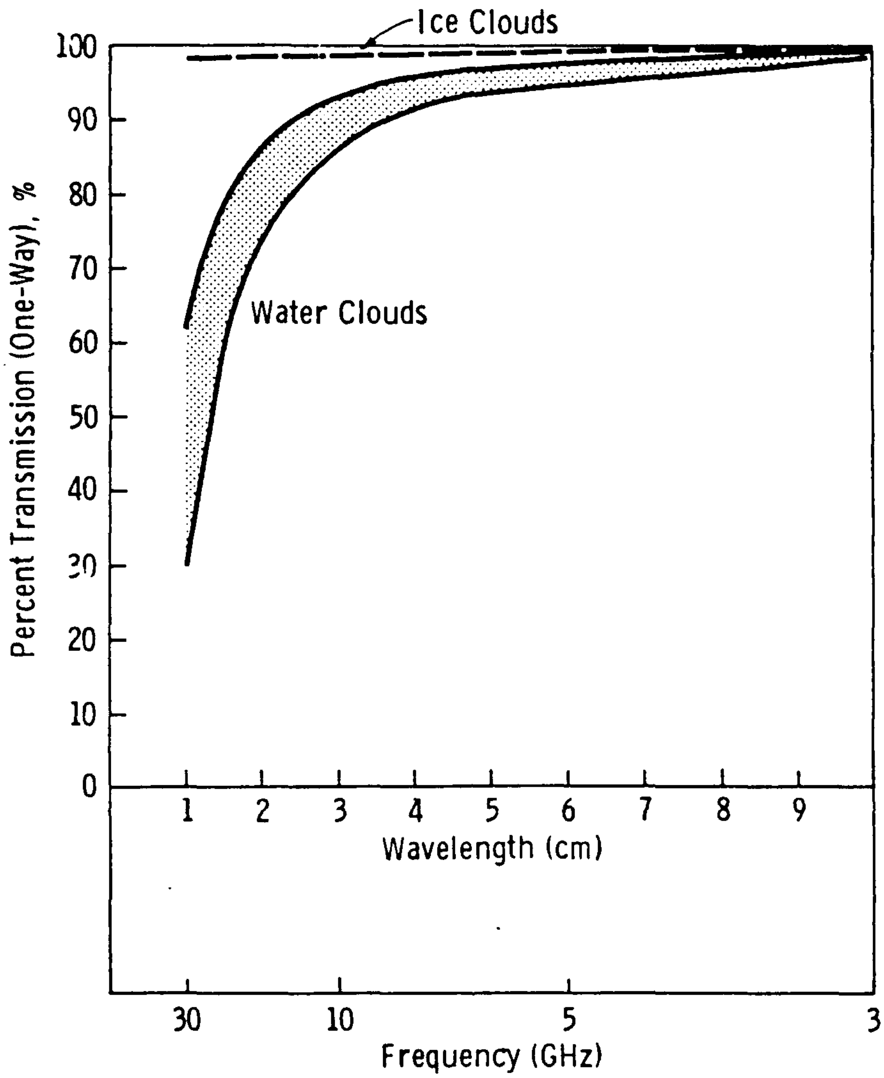

Figure 4. Effect of Clouds on Transmission from Space to Ground (36:2)

proficiency of the controllers and users in peacetime, while also providing minimum coverage during the initial stages of any worldwide conflict. More satellites can be inserted into orbit as needed. The expected life of each satellite is three years due to the long life of the electrical power by which attitude is controlled.

On-alert ground spares, teamed with the Pegasus booster, would give the system the most flexibility in satellite replacement, such as orbits and inclinations. Yet, on-alert spares require facilities near or on air bases that can launch the Pegasus for storage and testing. This option is very costly in construction and maintenance and goes against the constraint of timely development and maximum use of existing equipment/facilities. Further, on-orbit spares in a high parking orbit require enough fuel to do several plane changes in order to maneuver the satellite into a vacant spot in the constellation or into a position where usable intelligence can be gathered. This system, using electric propulsion, has high specific impulse yet low thrust, so quick plane changes are nearly impossible. Therefore, the system will have four on-orbit spares, in a standby mode, that are in close proximity to the working satellites. There will also be a total of 12 ground spares in storage that can be launched within two weeks in case of satellite failure/attack or reduced revisit time is required.

The system will have a total of 20 satellites in orbit and on the ground. These satellites, if all are placed into orbit, are almost the maximum number of satellites that the Mission Control Crews (MCC), who are monitoring the constellation, can handle (see next section: Mission Control Component). If more crews are added, more satellites can be in the constellation. Yet, it is improbable that any conflict will require more than 20 satellites in orbit at any one time. An analysis by Lockheed showed that 14 low-altitude tactical satellites would have been sufficient in one calendar year in order to monitor the Viet Nam conflict (20). During any conflict, more satellites will be produced before all 20 satellites in the proposed system can be rendered inoperable.

Mission Control Component. The satellite can be controlled from the field, but the primary controllers will be located at the Consolidated Space Operations Center (CSOC) who will utilize the Air Force Satellite Control Network (AFSCN). Controlling will consist of housekeeping, such as station-keeping, health and status checks, payload maintenance, and coordination of payload utilization between theaters. Much of the satellite evaluation will be automated in conjunction with MCC automation, yet manning will have to increase at the MCCs in order to accommodate the added constellation. An analysis by McDonnell-Douglas estimated that five 5-man crews need to be added for a constellation of up to 21 satellites. This takes into account surge activities, shorter revisit times, and multiple theaters (21).

Ground Receiving Component.[14] The proposed DMSP Mark IVB Tactical Terminal (TACTERM) will be the main ground equipment. This is an upgrade of the existing Mark IV and will be available for employment in the early 1990s. The TACTERM is a state-of-the-art computer processing system that is MIST compatible, yet is more capable than the MIST (21). It will be able to have a separate interactive workstation for transmitting commands and receiving data from the satellite[15]. TACTERMs will be located throughout the theater down to division/brigade/battery level, wherever the lowest level with a planning

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[14]LEO satellites have one significant impact on ground terminals. Because they pass overhead rapidly, their dynamics significantly impact ground terminal design. Typical ground terminals for LEO satellites require a good quality tracking antenna to follow the satellite. Also, receivers must have good dynamic range to track the doppler shift in the data link. All terminals described here are capable of handling data from a satellite in LEO.

[15]Defense Systems, Inc. has demonstrated PC-sized satellite ground control equipment that could be easily utilized in the field.

staff is located in that theater of operations. A planning staff is required in order to effectively use the obtained reconnaissance and self-regulate the priority of targets within their area of concern. The satellite will be preprogrammed with sets of instructions that a user can select with codes. Basically, the user selects the task and inputs coordinates. Nevertheless, the user can also override the basic instructions for unusual requests. This gives the system flexibility and ease of use. The satellite's onboard computer also has a set of preprogrammed priorities. These priorities can also be overridden, if necessary, by the theater commander.

System 2. This tactical reconnaissance satellite system will employ a constellation of small satellites carrying single sensors launched by the Pegasus or Taurus booster into LEO and theater-based ground equipment.

This system assumes a moderate threat to the satellite. Further, there will be lead time to hostilities of several weeks.

Satellite.

Structure. There will be two structures in this system for two different payloads. Both structures will feature a modular bus supporting multiple payloads, orbits, and missions. They will also support modular payloads. Each structure is fully compatible with either the Pegasus or the Taurus launch vehicle. The smaller satellite, 670 lbs, will be able to support a sensor payload of up to 250 lb (21). And, the larger satellite, 985 lbs, will be able to handle a 468-lb sensor payload (20).

Attitude and Velocity Control. The satellites in this system will also use GPS as the primary means of position determination,

yet the satellite will use horizon and sun sensors as a backup scheme. The moderate system will use hydrazine thrusters to moderate attitude and velocity. A complete attitude and velocity control subsystem has been developed for less than 140 lbs (21).

Electrical Power. The satellite that will carry the multispectral sensor will utilize a power system of solar arrays and batteries. This implies that there must also be power conditioning equipment for power conversion, regulation, and protection of circuits for high voltages and currents; load control equipment for controlling and distributing power as required; a solar array power transfer unit for transferring the power of the solar arrays to the main bus; and shunt dissipators to eliminate excess power produced by the solar arrays. It will require a 25-ft^2 array of stacked silicon on germanium cells[16]. The solar array will be the DARPA-developed inflatable array that use amorphous silicon solar cells. The array will be rolled out from the satellite then will harden and cure in space (39:78). This will reduce some weight, but more importantly reduce space requirements which are at a premium atop a Pegasus booster. This satellite will also have two 24-amp-hr High-Energy-Density Rechargeable Batteries (HEDR-B). These batteries are one-fifth the weight of typical NiCd batteries, yet produce the same amount of energy (10:593). This system will be

[16]A stacked silicon on germanium solar cell is about twice as efficient as a standard silicon cell (30 percent efficiency). The silicon and germanium sense different frequencies of radiation, so more of the incident radiant energy is converted to electrical power. The energy not absorbed by the silicon passes through so that the second layer of germanium can absorb the energy. This allows for stacking of the material and thus requires less array space (15).

able to produce 500 watts for the sensor and other electrical requirements.

The power source for the satellite with the SAR sensor onboard is a radioisotope thermal generator (RTG). The heat energy released by the decay of Pu-238 runs a liquid metal potassium Rankine cycle engine. The engine does work which produces electricity at such levels that will produce the 1.5 kW of electricity needed for the satellite. This type of Rankine cycle engine requires less radiator area because it works at very high temperatures (which means that a lot of excess heat need not be dissipated), and, therefore, weighs much less than a typical Rankine cycle (10:605). Although not space proven, this type of power source has been successfully employed in space. Further, this system appears to have no potential difficulties in being deployed in space.

Payload. Since the sensor payloads represent the minimum system that will meet the system requirements, then the payload will not change between alternative systems. Again, more capable sensors could be substituted, with an increase in cost, yet the proposed sensors are able to meet the requirements for a Tac Recce system.

Launch Vehicle. The satellite carrying the multispectral imager will be launched by the Pegasus booster, while the satellite carrying the SAR, and the nuclear power source, will be launched by the Taurus booster. The size and weight of the nuclear power source precludes the use of the Pegasus launch vehicle, while the advanced technology solar arrays allow the use of Pegasus for the other payload.

Basing. The same four satellites in the same orbits will be used in this system. Eight more satellites will be stored on the ground,

and can be deployed in one month (proposed Taurus launch capability). This system assumes a reduced threat from that speculated in System 1, so satellite attrition is less likely and less satellites are required. Again, during conflict more satellites will be produced. Nevertheless, revisit times may increase due to the launch delay and lack of on-orbit spares. This increase should never reach more than the 12-hour revisit limit contained in the system requirements, because two satellites should always be in operation. Satellite life is estimated to be 1-2 years. This is due to the low altitude and limited maneuvering fuel.

Ground Receiving Component. The main ground equipment for this system is the MIST. It is proven and already employed. An extra terminal that will handle Tac Recce requests and products will be added to the existing hardware. No new MIST vans will be procured.

System 3. This tactical reconnaissance satellite system will employ a constellation of small satellites carrying single sensors launched by the Taurus booster into LEO and a single-point, theater-based ground receiving station.

This system assumes that the probability of successful satellite attack is very low, therefore satellite survivability is not a priority. Further, enough lead time is assumed to be available in order to replace aged satellites in orbit.

Satellite.

Structure. This structure will also feature a modular bus supporting multiple payloads, orbits, and missions. It will also support modular payloads. This will also be a cost reduction scheme. The structure is fully compatible with the Taurus launch vehicle. Like the other systems, this structure, as well as every other component of

the system, will be constructed with proven high-strength, low-cost materials already available.

Attitude and Velocity Control. This system will utilize the same equipment as System 2.

Electrical Power. All electrical needs on both types of payloads will be powered by solar arrays and batteries. The arrays will be the standard P-N silicon photovoltaic cells. The multispectral imager satellite will need 50 ft^2 of array, while the SAR satellite will need 150 ft^2. These arrays will be stowed for launch and deployed using present systems, such as unfolding. For periods of eclipse, the imager satellite will use two 24-amp-hour NiCd batteries, while the SAR will use six (20). The standard associated electrical systems will also be present.

Launch Vehicle. The Taurus booster will insert both types of sensor payloads into orbit.

Basing. This system will employ four satellites in the aforementioned orbit and altitude. This system will have no spares, and each satellite will be replaced as needed. Each replacement satellite will be produced then launched within a year. It should be noted that with only four satellites in orbit, even with reduced anti-satellite threats, revisit times are likely to increase with any satellite failure/malfunction. This increase may, at times, exceed the 12-hour maximum revisit time in the system requirements.

Mission Control Component. In this system, with only four satellites in orbit and a long lead time to place more satellites in orbit, MCC manning need not be expanded. Because of the high level of automation built into the system and the ability of ground receiving

units in the field to control the satellites, present crews will be able to handle the housekeeping requirements of the system.

Ground Receiving Component. The MIST, located at the theater commander's headquarters, will be augmented with one PC-based terminal. This location will handle all Tac Recce requests and products.

Preference Chart

The Preference Chart (see Table 1) is the method by which criteria are ranked and assigned a weight relative to their importance to the system. The criteria listed in the table are "judged to be useful dimensions on which to rate the relative worth of potential system designs" (4:206). In other words, the system alternatives will be evaluated against the criteria in order to determine the best alternative.

The first criterion in the table is *Launch*. This represents the requirement of launch versatility. The alternative systems are evaluated on how versatile its launch system is in terms of type of orbits that can be achieved, altitudes that can be reached, and inclinations that can be achieved. A system that can achieve any orbit, altitude, and inclination would be very versatile in its mission of inserting satellite payloads.

The second criterion is *Responsiveness*. This criterion takes into account not only the time it takes for data to reach the end user from the satellite, but also the revisit interval between satellite passes. So, this measures the overall time the system takes to fulfill a request. For example, all else being equal, a system with a revisit interval of 3 hours is more responsive than a system with an 8-hour revisit.

The third criterion is *Reliability*. This measures the system's ability to successfully perform its mission over its lifetime. This criteria

Table 1. Preference Chart

Criteria	Launch	Responsiveness	Reliability	Survivability	Replacement Time	User Control	Total	Weight
Launch	\	=	=	>	>	=	12	2
Responsiveness	=	\	<	>	>	>	12	2
Reliability	=	>	\	>	>	>	14	2.3
Survivability	<	<	<	\	=	<	6	1
Replacement Time	<	<	<	=	\	>	8	1.3
User Control	=	<	<	>	<	\	8	1.3

NOTE:
Vertical axis criteria compared to horizontal axis such that:

- >> is much more important (4 points)
- > is more important (3 points)
- = is relatively equal (2 points)
- < is less important (1 point)
- << is much less important (0 points)

also examines the degree of advanced technology and its effect on the system's final reliability. For example, a system using industry standard, space-proven components is compared with a system with new technology (or components that have not been used together in the past) that, theoretically, should have better reliability.

The fourth criterion is *Survivability*. This criterion looks at the overall system's ability to negate attack. Each system is judged by the degree of protection and number of components that are survivable. For example, satellite hardening, large constellation, and lack of large solar arrays make a system more survivable than a single solar-powered satellite. Survivability concerns are also evaluated in the ground

receiving stations (multiple mobile receivers) and launch systems (mobile or multiple deployment capabilities).

The fifth criterion is Replacement *Time*. This is the criterion that measures the time the system takes to replace a satellite which has failed, reached the end of its useful life, or has been degraded through attack. This criterion takes into account an alternative's launch system and basing options.

The last criterion in the table is *User Control*. This evaluates the level of control that a typical requestor has over the targeting by the satellite. It is assumed that the lower the level of control of the satellite, the greater the control of the requestor.

It is obvious that some potential criteria are not stated in the table. Since the sensors remain the same between each alternative, to judge the alternatives by *resolution*, *area of coverage*, and other sensor specific criteria would not be meaningful. There would be no way in which to distinguish between the alternatives, so these kinds of criteria have been left out.

The relative importance between criteria is read from the criteria on the left as it relates to the criteria across the top of the table. This relative importance is taken from discussions with Maj Blain Harvey, Army Space Command; Maj Charles Banning, Air Force Space Systems Division; and Mr. Frank Moon, Army Space Institute.

The criteria weights were determined by dividing the lowest score into all the scores. These weights give the overall relative importance of each criterion and will be used in evaluating the alternatives.

Systems Utility Function

The measure defining the expectations of system performance for each of the criteria is outlined in the Systems Utility Function (see Table 2). This table displays the performance requirements of a system in each of the criterion categories which are considered to be either exceptional, above average, average, below average, or barely acceptable.

The range of "performance" is listed in the table for each criteria. Under the criterion of *Reliability*, performance is the probability that the system's components will not fail over their useful life. Under *Launch*, performance is the system's capability to attain certain orbits, altitudes, and inclinations, where "Fixed" relates to a launch system achieving fixed orbits, altitudes, or inclinations and "All" relates to achieving all possible orbits, altitudes, and inclinations. Under *Responsiveness*, performance is measured by the amount of time a requestor has to wait in order to get target coverage, whether for data transmission and relay delays or revisit intervals. Under *User Control*, performance is the level at which inputs to the satellite are controlled. Under *Replacement Time*, performance is measured by the amount of time it takes the system to replace a satellite in orbit. Under *Survivability*, performance is the amount of system components that are designed with techniques that ensure that the system survives attack.

The rating is a numerical value assigned to each alternative's criteria performance. This number will relate how a system's expected performance measures up with the desired performance. This will be used in evaluating the alternatives.

Table 2. Systems Utility Function

WEIGHT	RATING	0 1	2 3	4 5	6 7	8 9
	CRITERIA	BARELY ACCEPTABLE	BELOW AVERAGE	AVERAGE	ABOVE AVERAGE	EXCEPTIONAL
2.3	Reliability	70%	80%	90%	95%	99%
2	Launch	Fixed	Few	Some	Most	All
2	Responsiveness	12-hr	8-hr	3-hr	2-hr	1-hr
1.3	User Control	Theater CC	Corp CC	Battalion CC	Brigade CC	Company CC
1.3	Replacement Time	1 year	1 month	8 days	72 hours	1 hour
1	Survivability	No System Component	Few System Components	Some System Components	Most System Components	All System Components

Systems Simulation Chart

Expected performance of each alternative satellite system is given in the Systems Simulation Chart (see Table 3). Since each alternative is a totally new system, future performance can only be estimated. This estimation is tempered with a level of confidence assigned to each value. Again, this level of confidence is a "best guess" based on system complexity, level of advanced technology incorporated, and the typical scenario in which the system will be used.

The factor is the correction to the rating from the Systems Utility Function for the level of confidence. This correction will be used in evaluating the alternatives.

In summary, this chapter established system requirements and constraints, listed system options, weighted criteria, established desired performance standards, and expressed the confidence of expected performance, all of which will be used in the final evaluation.

Table 3. Systems Simulation Chart

CRITERIA	ALTERNATIVE	EXPECTED PERFORMANCE	CONFIDENCE
Reliability	System 1	90%	C
	System 2	90%	C
	System 3	90%	VC
Launch	System 1	Most	VC
	System 2	Most	VC
	System 3	Most	VC
Responsiveness	System 1	3-hr	VC
	System 2	3-hr	C
	System 3	3-hr	LC
User Control	System 1	Brigade	VC
	System 2	Brigade	VC
	System 3	Theater	VC
Replacement Time	System 1	72 hours	VC
	System 2	8 days	VC
	System 3	1 year	VC
Survivability	System 1	Most	VC
	System 2	Some	VC
	System 3	Few	VC

Note:

Code	Level	Factor
VC	Very Confident	0.9
C	Confident	0.6
LC	Little Confidence	0.3
NC	No Confidence	0.1

IV. Conclusions and Recommendations

In the Systematic Systems Approach, the Evaluation Matrix takes the criteria weights from the Preference Chart, the ratings from the Systems Utility Function, and the confidences from the Systems Simulation Chart and determines a ranking between alternatives.

Evaluation Matrix (4:220-225)

The Evaluation Matrix takes each feasible alternative and measures it against each criterion (see Table 4). The first column under each alternative is *Relative Rating*. This value represents how the alternative's expected performance compares with desired performance for each criteria. This value comes from the Systems Utility Function (Table 2). The second column shows the level of *Confidence*, from the Systems Simulation Chart (Table 3), that the alternative system will meet its expected performance standards. The third column is *System Utility* and measures the contribution to the overall utility of the system for each criteria. This value is determined by multiplying the Relative Rating by the weight of the criteria. The last column under each alternative is *Discounted Utility*. This value represents the criteria's contribution to the system utility tempered by the perceived accuracy of the expected system performance. This value is determined by multiplying the System Utility value by the factor associated with the level of confidence (factors are listed under Table 3 and Table 4).

With these utility values determined, a ranking is possible between the alternatives. The *Total Value* is the overall relative utility of the

Table 4. Evaluation Matrix

Criteria (Weight)	Feasible Alternative											
	System 1				System 2				System 3			
	R	C	U	D	R	C	U	D	R	C	U	D
Reliability (2.3)	5	C	11.5	6.9	5	C	11.5	6.9	5	VC	11.5	10.4
Launch (2)	7	VC	14	12.6	7	VC	14	12.6	7	VC	14	12.6
Responsiveness (2)	5	VC	10	9	5	C	10	6	5	LC	10	3
User Control (1.3)	7	VC	9.1	8.2	7	VC	9.1	8.2	1	VC	1.3	1.2
Replacement Time (1.3)	7	VC	9.1	8.2	5	VC	6.5	5.9	1	VC	1.3	1.2
Survivability (1)	7	VC	7	6.3	5	VC	5	4.5	3	VC	3	2.7
Total Value	60.7				56.1				41.1			
Discounted Value	50.3				44.1				31.1			
Overall Confidence	82.9%				78.6%				75.7%			

NOTE: R = Relative Rating VC = .9
C = Confidence C = .6
U = System Utility LC = .3
D = Discounted Utility

system and is the summation of the values in the System Utility column. The *Discounted Value* is the overall utility of the system tempered by the accuracy of the expected performance of the system. This value is determined by adding the values in the *Discounted Utility* column. The *Overall Confidence* represents the overall perceived system accuracy of the expected system performance. This value is determined by dividing the *Discounted Value* by the *Total Value* of each alternative system.

Results

The System 1 alternative has the highest *Total Value* (60.7), the highest *Discounted Value* (50.3), and the highest *Overall Confidence* (82.9%). System 2 ranked second and System 3 third in all three values.

Costs

A detailed cost analysis is left for another study. Further, costs associated with the equipment discussed in this study are variable due to level of technology and future production costs. Therefore, realistically pricing the total systems would be difficult. Yet, a general appreciation of the relationship between the alternative systems in terms of cost is desirable.

The satellite in System 3 is similar in level of technology to the Army Tactical Surveillance Satellite recently proposed by the Army's Advanced Technology Directorate (27). Both utilize readily available, space-proven components. Therefore, System 3's satellite can be said to cost about the same as the Army's satellite, approximately $7-8 million.

The satellite in System 1, in contrast, employs advanced concepts which would increase the cost of the system. For example, nuclear

power would nominally double the cost of the satellite.[11] Similarly, the other advanced components could be very expensive because they need to be developed, demonstrated, and/or space proven.

The satellite in System 2 uses some more advanced technology components than System 3's satellite, yet not as many and not as advanced as those in System 1's satellite. System 2's satellite is realistically midway between the cost of the other two systems. Further, in this general cost outlook, System 2 overall is midway between the more expensive System 1 and the least costly System 3.

Launch costs are also difficult to ascertain for the complete system. System 1 utilizes the Pegasus booster which costs approximately $6.3 million to place a satellite into orbit, while the Taurus, which is employed in System 3, would cost $15 million. System 1's constellation would cost $50.4 million, yet the ground spares imply that other boosters are readily available for use. System 3's constellation would cost $60 million, yet with no spares, spare boosters would not be necessarily part of the initial cost estimates.

In terms of the mission control component, all of the alternative systems would require expanded workload in the Mission Control Center (MCC). System 1 would require another crew on shift to monitor and control the constellation, while System 3, with a limited constellation and long lead time for replacement, would simply represent added duties to the existing crews. This implies the added costs of extra personnel and training would increase the overall system cost of System 1 dramatically.

[11] In order to provide the needed power for the imager satellite, the least expensive nuclear source would cost $5 million, while the SAR satellite's nuclear power source would cost $15 million. The upper limit would be around $75 million just for the power source.

The ground receiving component of the alternative systems also represents an area where costs greatly differ between the alternatives. System 1 would utilize many upgraded communications equipment, which still need to be procured, while System 3 uses one already existing piece of equipment within the theater. This again represents a significant amount of cost.

In summary, the alternative systems have differing capabilities which are reflected in a wide range of costs. If System 3 is taken to be the baseline in comparing costs, System 1 could cost approximately ten times as much and System 2, five times as much. If System 3's overall implementation cost is approximately $100 million, then System 1 would cost $1 billion, not including recurring costs such as training, maintenance, and personnel. These figures are only significant in any attempt to include a tactical reconnaissance satellite system into the federal budget.

Recommendations

The mission of tactical reconnaissance is achievable through a constellation of small tactical satellites. All the alternatives are very flexible in design and represent segments of a continuum which could be modified to fit the changing political face of the world. If mission accomplishment and threats are the prime motivators, then System 1 is clearly the best alternative to employ. If cost is a constraint, then System 2 would be a good compromise. If funds are limited, then System 3 could be acquired and expanded in the future. Under any political scenario, a viable tactical reconnaissance satellite system could

be procured that will accomplish the mission with the flexibility to monitor, and adapt with, the changing world.

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Vita

Captain John D.T. Severance was born on 13 January 1959 in Manila, Philippines. His family moved to the United States when he was five years old, and lived in Long Island, New York, until finally settling down in Chula Vista, California when he was twelve. He graduated from Hilltop High School in Chula Vista in 1977 and attended the U.S. Air Force Academy, graduating with a Bachelor of Science in Behavioral Science (specialty: Human Factors Engineering) in May 1981. Upon graduation, he received a regular commission in the USAF and attended Undergraduate Navigator Training at Mather AFB, CA. He graduated as a distinguished graduate in February 1982 and attended RF-4 RTU at Bergstrom AFB, TX. After completing RTU, he went on his first operational tour as a Weapon Systems Officer with the 15th Tactical Reconnaissance Squadron, Kadena AB, Japan. In 1986, he went back to the 67th Tactical Reconnaissance Wing at Bergstrom to become a flying instructor. He eventually became an academic instructor in the 67th Tactical Training Squadron where he was the Chief of Academics. There he was responsible for the content of all of the lesson plans, the scheduling of the courses and instructors, and instructor proficiency until entering the School of Engineering, Air Force Institute of Technology, in May 1989.

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Tactical reconnaissance is a much needed wartime asset, yet with the deactivation of all active-duty RF-4C squadrons world-wide there appears to be a gap in this country's war-fighting capability. This study proposes a system which utilizes a constellation of small tactical satellites and mobile ground receiving stations that can fulfill the tactical reconnaissance mission. A literature review gives background information on resolution variables, the RF-4C, space reconnaissance, and sensing technologies. After defining system requirements and constraints, a basic system concept is determined. Three alternative systems, separated mostly by threat scenario, technology, and cost, are evaluated using Athey's "Systematic Systems Approach." The selected satellite's sensors consist of a multispectral imager and a SAR. The satellite will be launched by the Pegasus air-launched booster for flexibility, survivability, and responsiveness. Initially, four satellites will be placed in a circular LEO for training, with four more in-orbit spares, although, twelve more will be stored as ground spares and can be placed into any LEO that is needed. The ground receiving unit will be the Mark IVB tactical terminal which will be located in communications vans at the lowest echelon with a planning staff wherever troops are deployed.

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